REDUCING THE RISK OF MAJOR BLACKOUTS THROUGH IMPROVED POWER SYSTEM VISUALIZATION

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Abstract – Many blackouts occur with time scales that would permit emergency control by the operators. However, in order to perform this control the operators need to quickly know the state of system and implement timely, corrective control actions. This paper describes several visualization techniques that can be used to provide this information. Techniques discussed include the use of dynamically sized pie charts on transmission lines, the use of transmission line flow animation, and the use of contouring.

Keywords: Power systems, data visualization, real-time operations, reducing blackout risk

1 INTRODUCTION

Around the world the recent large-scale blackouts have dramatically demonstrated that even with modern energy management systems (EMSs) cascading blackouts are still not a relic from the past. Even in the early part of the 21st century a few untrimmed trees are still capable of putting tens of millions in the dark! In response to these events some engineers have argued that such big blackouts are inevitable and hence should be accepted as a fact of life, perhaps even acting as a "constructive force" [1]. While all engineers would undoubtedly agree that the probability of future blackouts can never be reduced to zero, most would agree that this probability can, and should, be reduced.

In North America a list of recommendations for reducing this probability was included in the final report for the August 14, 2003 blackout [2], with a one year later progress report on the actions actually implemented given in [3]. These recommendations covered a wide range of topics, from institutional changes by government agencies to changes in protection system plans and practices. It is clear that a number of changes can be made in several different areas to decrease the risk of future blackouts. The purpose for this paper is to explore one of these areas – the role improved power system visualization in the control centers can play in reducing blackout risk.

2 BLACKOUT TIME FRAMES

While much of the operation of the power grid is automated, this degree of automation is much lower than most people realize. Human operators and engineers are still very much "in the loop." Of course, whether or not operator actions can actually prevent or mitigate a potentially cascading blackout depends upon the time frame of event. Some events, such as earthquakes, can cause massive damage to the electric grid within seconds. Whether the system survives depends entirely upon the actions of automatic devices such as relays. Examples of such events include the Northridge, California Earthquake in January 1994, in which extensive transmission system losses resulted in the rapid breakup of the entire Western North America grid (WECC) [4], and the earthquake in Kobe, Japan in January 1995 which quickly destroyed numerous electric power facilities [5]. The immediate event is over before any human operator could intervene.

On the other hand, massive blackouts can be caused by relatively slow weather phenomena, such as ice storms and hurricanes, in which the operators have plenty of time to act, but are overwhelmed by the magnitude of the damage to the transmission grid. For example, an ice storm in January 1998 in the northeast portion of North America resulted in the collapse of more than 770 transmission towers causing a blackout affecting more than 1.5 million people in Canada [4].

However, many, if not most, major blackouts or potentially major blackouts occur with time frames of several minutes to a few dozen minutes – time frames that permit operator intervention. The reason for this is the combined time constants of the underlying dynamics. These dynamics often include the heating (and hence the sag) of transmission lines, the operation of LTC taps, and the generator maximum excitation system limiters [6], all of which range from many seconds to minutes. For example the time frame for the July 27, 1987 Tokyo blackout was about twenty minutes [7], the time frame for the August 10, 1996 WECC blackout was about six minutes [8], while the time frame for the September 28, 2003 Italian blackout was about twenty five minutes [9].

Of the set of blackouts that have time frames allowing for operator intervention, practically all could be mitigated through corrective, though perhaps extreme, control. Quickly shedding load at the right location(s), changing generation, or opening tie-lines may be the only solution. For example, a conclusion of [10] with respect to the July 6, 1999 event on the Delmarva Peninsula was an imminent voltage collapse was averted by operator initiated load shedding load within minutes of the initiating contingency. However, these are obviously responses that would not be under taken lightly, but because of the time constraints a decision must be made quickly. The seconds and minutes spent figuring out what to do is time no longer available to actually get it done.

A particularly germane example is the August 14, 2003 blackout. Referring to [2], approximately 60 minutes passed between the loss of the first 345 kV line at 15:05 Eastern Daylight Time (EDT) until the start of the large cascade initiated through the loss of the Sammis-Star 345 kV line at 16:05 EDT. Even when one subtracts off the 30 minutes of time from this first event until the affected utilities realized there was a problem thirty minutes of time were still available for corrective control. And the conclusion on page 70 of [2] was "if manual or automatic load-shedding of 1,500 MW had occurred with the Cleveland-Akron area before that outage (referring to the loss of Sammis-Star), the blackout could have been averted." Unfortunately, during this critical time period no corrective control was actually done. A key question of the investigation was why?

3 EXTREME EMERGENCY OPERATION

The answer, at least in part from [2], was inadequate situational awareness at FirstEnergy, and a failure by other reliability organizations (including MISO) to provide FirstEnergy with effective diagnostic support. In short, during the critical 30 minutes during which corrective control could have been initiated nobody really knew what was going on. FirstEnergy's alarming application had failed, they had no mapboard type display, and their SCADA console displays were refreshing slowly, while MISO did not have one-line displays showing the real-time system status for the FirstEnergy system. Given this situation, a natural question to ask is are current EMSs designed to really help operators make crucial, time-critical decisions during periods of emergency operation? What tools would really be available to determine within several minutes whether or not to shed potentially large amounts of firm load?

To begin to answer these questions it is useful consider how the control room environment would likely differ during an extreme emergency from normal operation. First, most, if not all, of the advanced network analysis applications would likely not be available. Because of a potentially rapidly changing system state, measurement time-skew, and no longer valid modeling assumptions, it is likely the state estimator (SE) would no longer be converging. Even if it did converge by the time a solution became available it would be out-of-date. Without an SE solution contingency analysis (CA) won't run, and even if it ran by the time it solved it also would be out-of-date. And even if it solved the operators would be overwhelmed by hundreds or thousands of CA violations. Likewise, power flow or optimal power flow studies would take too long to setup, and would also be out-of-date by the time they were completed. Hence during this critical time decisions probably would need to be made based solely upon real-time measurements from SCADA, supplemented perhaps with alternative systems such as phasor measurement units (PMUs) [11].

Second, during emergency operation the system state could be quite different from anything the operators and engineers had previously seen. Flows on key transmission lines might be reversed, and the voltage profile might be substantially different from the expected. Intuition gained from years of operational experience may no longer be correct, and may actually be counter-productive. From a visualization perspective this means that information about the system state must be clearly presented to let the operator quickly assess the actual system condition, even when it deviates substantially from what they expect.

Third, the level of stress for all control room participants could be high, and "when high levels of stress exist, errors are more likely to occur" (pp. 480, [12]). It is well-validated that expert operators are more immune than novices from the negative effects of stress, but this effect only occurs when the experts are presented with situations that match their experience. Hence, "pure expertise in routine performance is not sufficient to provide an effective stress response" (pp. 490, [12]). What is needed is training for extreme emergencies.

Fourth, the number of "decision makers" in the control room may be greater than during times of normal operation. While operators usually have the authority to unilaterally shed load, mostly likely such a crucial decision would be make through a collaborative process. Since many emergency events occur during normal business (i.e., when the load is highest) in a typical control room the set of decision makers usually includes operators, supervisors, operational engineers and perhaps members of management, all of whom may need to quickly assess the system state. Therefore visualizations may need to be presented to at least small groups, meaning single CRT views may not be adequate. But because of a phenomenon known as "tunnel vision", in which during time of stress an operator's attention becomes quite narrowly focused (pp. 147, [14]), extremely large "mapboard" type projections should be used with care.

The next section presents several visualizations that could be useful to operators during times of emergency operation, with the ultimate goal of helping to prevent blackouts. However, before moving into this section two observations are warranted. First, information visualization requires real-time data. If an SE solution is unavailable then presenting overview visualizations requires lots of SCADA measurements. And in the likely case in which the problem spans multiple control areas then this information must be shared between control areas. The remainder of the paper assumes that this information is available. The techniques could still be used with less information but with loss of fidelity.

Second, visualizations designed for emergency operation may not be perceived as useful or desirable for normal, routine operations. When the system is operating as expected the operators know what is going on, and hence have no need for displays to rapidly tell them what they already know. Therefore the visualizations presented in the next sections should be thought of as supplemental to the routine displays. They need not be continually shown, but should be easily accessible since emergencies tend to occur unexpectedly. Also, scenario-based emergency training is needed so the operators know how to use them should the need arise.

4 VISUALIZATION AND PROBLEM DIAGNOSIS

Traditionally in an EMS system operational quantities, such as power flows and voltages, are usually represented as either analog fields on a set of substation one-line diagrams, or numeric fields on tabular displays. Dashed lines might be used to represent device status, while fonts may change color to indicate limit violations. An overviews of the system had only been available on a static map board with the only dynamic data shown using different colored lights. While such a representation might be desired for normal operation, or even during slowly developing system emergencies, the assertion of this paper is it is inadequate for allowing operators to quickly comprehend a rapidly, and perhaps unexpectedly changing system state. An alternative is to provide wide-scale visualizations that take advantage of the animation capabilities of modern computers to graphically show important system quantities such the transmission line/transformer (line) flow values, NERC flowgate values, and bus voltages.

4.1 Line Pie Charts

One visualization technique that has proven useful for quickly indicating the location of overloads/outages in a transmission network has been the use of pie charts in which the percent fill of each pie chart is equal to the percentage loading on the line [13]. Optionally, a numeric text could also be superimposed on the pie chart to indicate the exact percentage. For displays with relatively few lines, where each individual line's pie chart can be viewed with sufficient detail, such pie charts can quickly provide an overview of the system loading. If desired, different color shadings could also be used with the pie charts to highlight those devices loaded above some threshold percentage.

However, for larger network overview displays there is insufficient space to show each individual pie chart. Instead, a supplementary technique is to dynamically size the pie-charts based upon the line's percentage loading. In this approach the percentage fill in each pie-chart is still equal to the percentage loading on the line, but the size and color of the pie-chart can be dynamically sized when the loading rises above a specified threshold. By increasing the size and/or changing the color of the pie charts only for the small number of elements loaded above a critical threshold, the user's attention can be focused on those elements near or exceeding their limits even of displays with lots of other pie charts. The overloaded elements appear to "pop-out" on the display. This dynamic sizing/color changing can also be used to indicate open transmission lines.

From a human factors viewpoint, the underlying mechanism that causes information to pop-out is called preattentive processing (pp. 149-158, [14]). One of the advantages of using visualizations that take advantage of preattentive processing is the time taken to find the desired object on the display is essentially independent of the number of other elements on the display (known as "distractors"). Size, color and motion are three examples of features that are preattentively processed.

Figure 1 shows an example of this technique for a case simulating the power flows in Northeast Ohio immediately prior to the first 345 kV line outage on August 14th, 2003. Overall the display shows slightly less than 400 buses (mostly 138 and 345 kV), slightly more than 400 transmission line/transformer pie charts, and the pie chart for a single flowgate. The pie charts are dynamically sized/colored to be 10 times their normal size and colored orange for a percentage loading above 85% of their emergency limit, and to be twelve times their normal size and colored red for a loading above 100%. Note that the dynamic sizing immediately draws attention to the single line loaded at 87%.

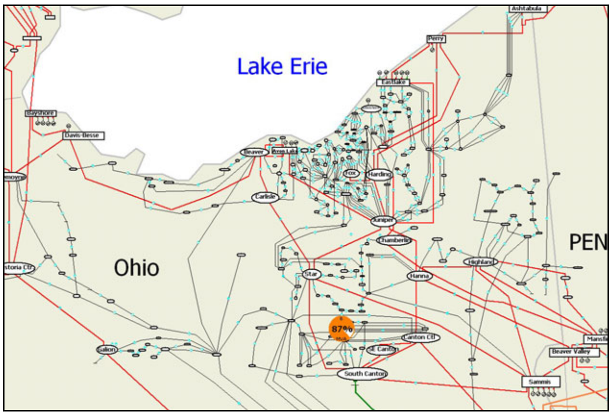

Figure 1: Pre-blackout Northeast Ohio Transmission

Figure 2 repeats the Figure 1 visualization after the loss of the first 345 kV line (Chamberlin-Harding) at 15:05 EDT. While the loss of this line did not cause any transmission line overloads, it did cause an overload on contingent flowgate #2265, which monitored the flow on the Star-Juniper 345 kV line for the contingent loss of the Hanna-Juniper 345 kV line. The large red pie chart immediately draws attention to this overload. The open transmission line's pie chart can also be dynamically sized and can have its color changed to draw attention. In Figure 2 the open Chamberlin-Harding 345 kV line is indicated by the large black pie chart with the green "X". Of course, other color combinations and symbols could be used. Note, on August 14th both of this events were initially missed by MISO and FirstEnergy.

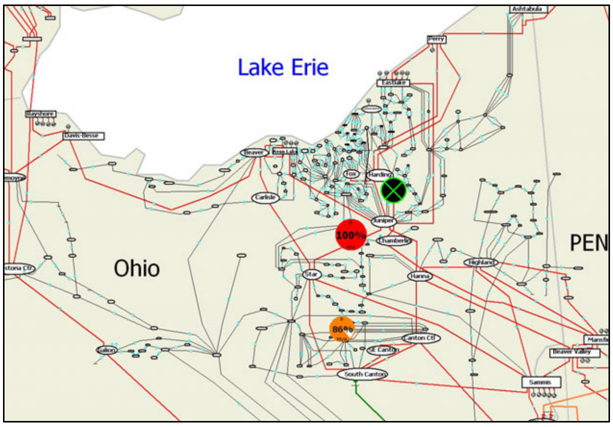

Figure 2: Northeast Ohio Transmission System Status after Loss of First 345 kV Line at 15:05 EDT

There are, however, several potential problems with the pie chart approach. First, care must be taken when applying resizing to devices that are designed to be regularly loaded at a high percentage level. Common examples of this are generator step-up transformers. Such transformers are designed to be regularly loaded at a high percentage of their ratings, but because of their radial connection, they are in no danger of overloading. A straightforward solution to this problem is to either not show pie charts on such devices or to specify that the pie charts should not be dynamically resized.

Second, the use of dynamically sized pie charts involves a tradeoff between making the pie charts large enough to draw attention, yet not too large so as to obscure other important one-line elements. This is illustrated in Figure 3, which shows the August 14th system at 15:51 EDT after three 345 kV lines and a number of 138 kV lines have opened. The large number of overloads/line outages would make it much more difficult for the operator to rapidly locate the most crucially overloaded devices. Of course, this is a characteristic of any approach that uses dynamically sized one-line elements, including the approach from [15] of dynamically increasing the line widths to indicate overloads.

One solution for this problem is to filter the display to highlight certain lines, and attenuate the display of other lines. For example, Figure 4 repeats the Figure 3 display except now the lower voltage lines are blended into the background, helping to focus attention just on the more critical 345 kV lines. Now it becomes clear that the Sammis-Star 345 kV line is overloaded, and that four 345 kV devices are open. Yet the lower voltage lines are still partially visible, helping both to provide context for the higher voltage lines and to allow continued monitoring of these lines.

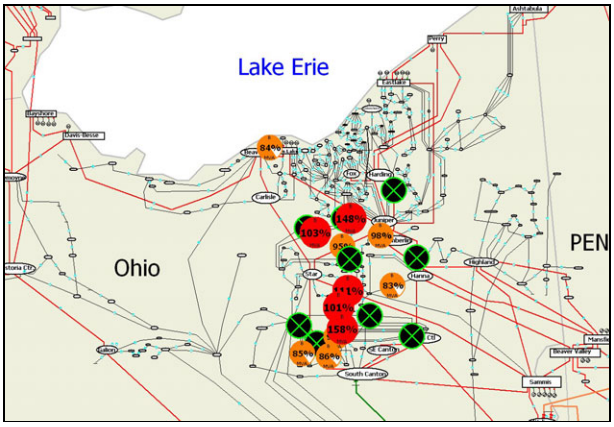

Figure 3: Transmission System at 15:51 EDT

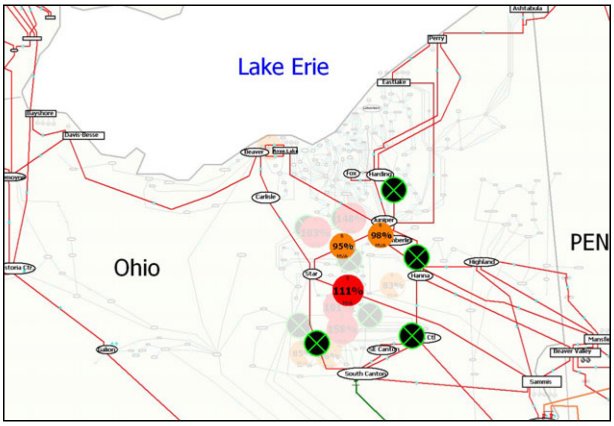

Figure 4: Filtered Figure 3 Display Highlight just the 345 kV Values

A second potential solution would be to proportionally reduce the amount of resizing as the display is zoomed. For example, a maximum zoom value for full resizing could be specified. Once the display is zoomed past this value the amount of pie chart resizing could be dynamically reduced until reaching some threshold value, such as the size of a normal pie chart. The visual effect during zooming is the resized pie chart remains the same size on the screen causing the overlap to eventually vanish. Figure 5 shows a zoomed view of the central portion of Figure 3 using with technique.

4.2 Animated Flows

Useful as the pie charts may be, they still to not provide any indication of the direction of flow. During emergency operation, in which historical flows may have reversed, quickly conveying this information could provide crucial. One technique for displaying line flows is to superimpose small arrows on the lines, with the arrow pointing in the direction of the MW flow, and the size of the arrow proportional to either the MW or MVA flow on the line [16]. The size and color of these arrows can also provide a visual reinforcement of the severity of the problem. For example, in Figure 6 the arrows on the overloaded Sammis-Star line are colored red, while the net direction of the power flow into the

Cleveland-Akron area could indicate a problem in that area.

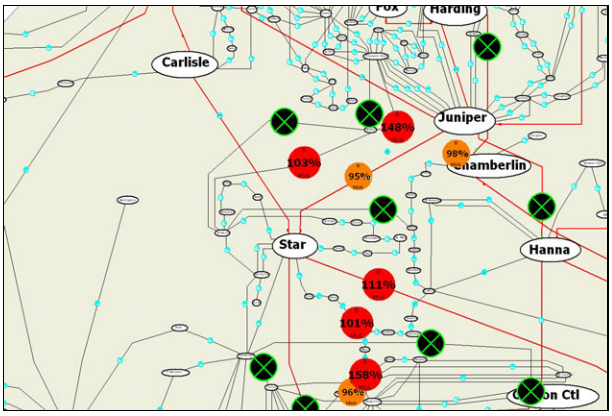

Figure 5: Zoomed View of Figure 3 with Dynamic Pie Chart Zoom Control

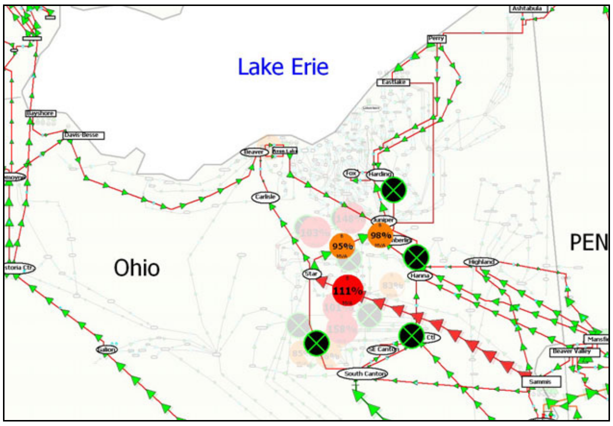

Figure 6: Transmission System at 15:51 EDT with Flow Arrows

To further emphasize the flow direction the flows themselves could also be animated. With modern computer equipment fairly smooth animations are possible even with rather large displays. For example the Figure 6 case can be animated at a rate of about ten times per second on a 1280 by 1024 pixel display. relatively large systems. The effect of the animation is to make the system appear to "come to life". Our experience has been that at a glance a user can gain deep insight into the actual flows occurring on the system. The use of panning, and zooming with conditional display of objects gives the user the ability to quickly study the flows even in a large system.

However, the application of such animated flows to larger systems has to be done with some care. It is certainly possible to create one-lines in which the presence of the animated flow arrows results in more clutter than insight. An example would be Figure 3. But if the view is filtered to just a particular voltage level, or zooming is utilized to focus on a particular portion of the grid, then the animated flow arrows can be quite helpful. The use of animation could also be restricted to just those lines of particular interest, taking advantage of the fact that motion is also preattentively processed provided the number of elements moving on the screen is small. Selective use of animation can also convey a sense of urgency to the operator. The lack of a sense of urgency to remove a line overload was one of the main reasons for the 2003 Italian Blackout (pp. 6 of [9]). Experimental results examining the impact of motion of flow visualization are presented in [17].

4.3 Contouring

In addition to visualizing flow-based quantities it is important to also rapidly convey bus voltage magnitudes. For decades power system engineers have used one-line diagrams with digital numerical displays next to each bus to represent bus-based values. The advantage of a numerical display is the results are highly accurate and are located next to the associated bus. The disadvantage is it not useful when one wants to examine the values at more than a handful of buses, say to find voltage patterns in the power system. In order to overcome this problem the use of bus voltage contouring is presented [18].

Contours have been used extensively for the display of spatially distributed continuous data in many other fields. However, there are three key issues with applying contouring to the display of power system voltage magnitudes. First, the bus voltages are not spatially continuous – the voltage magnitude data points only exist at distinct buses with no values in between. To address this issue virtual values must be created to span the entire two-dimensional contour region. The virtual value is a weighted average of nearby data points, with different averaging functions providing different results. Second, tap-changing transformers may introduce sudden changes in voltage. However, this issue can be addressed by setting up a contour in which one a small group of voltages levels are contoured. Third, voltages that are near one another on a diagram may not be “near” one another electrically. This issue can also be addressed by only contouring particular voltage levels, and perhaps by judicious construction of the contouring diagram. If a strictly geographical layout is used, normally buses of the same nominal voltage that are near each other geographically are also near electrically.

Once the virtual values are calculated a color-map is used to relate the numeric virtual value to a color for display on the screen. A wide variety of different color maps are possible, utilizing either a continuous or discrete scaling (for a useful discussion of color mappings see [19]). One common mapping is to use red for lower voltage values and blue for higher values, while another common mapping is the exact opposite.

Perceptually, contouring works well because the human visual system is well designed for detecting patterns. For example, Figure 7 shows a voltage contour of about 5600 bus voltages in the Mid0-Atantic portion of North America at about 15:00 EDT on August 14 using a blue to red discrete color mapping. At a glance the relatively low initial voltages in Ohio and Indiana are visible, with the extremely low voltages in Southern Indian due to line outages that occurred at about noon on August 14th. Figures 8 and 9 showed more zoomed views of Northern Ohio.

Human factors testing of power system voltage contours indicates they are useful both for increased speed and accuracy in problem diagnosis, particularly for situations with many voltage violations [20]. This occurs because color serves as an effective highlighting feature that attracts attention to an area of a display and reduces the size of the search space, thus allowing for the rapid localization of problem areas. In addition, the use of color contouring has the ability to create global or holistic properties in the display, which are in contrast to the local or component parts that exist. Global properties of objects depend on the interrelations between the component parts and generally refers to the Gestalt concept that the "whole is greater than the sum of its parts." Hence, color contouring may allow operators to assess the overall state of the system more readily (gain better situation awareness or develop a more accurate mental model) and therefore facilitate the choice of a more appropriate and timely corrective action.

Another advantage of contouring, which is impossible to show in a paper, is the images can be readily animated to quickly show the progression of the system over time (similar to what is done with animated weather maps). During an emergency this information could be used to rapidly convey the direction of the system state, and could also be used to rapidly bring late arriving people to the control room up-to-speed on what is going on.

However, one does need to be careful about trying to convey too much information in a single display. For example Figure 8 combines transmission system information (pie charts and flow arrows) with the contour. While this may be tolerable if there are just a few problems, as more problems develop it would become increasingly cluttered. Flow information is not shown in Figure 9. While not explored here, one potential solution to combining different types of information is the use of three dimensional displays [21].

In addition, the number of colors that should be optimally used in a display are bound by human limits of absolute judgment. In using color contours, an operator needs to differentiate between colors to understand what voltage value a color represents. Absolute judgment experiments have typically shown that errors begin to be made in discrimination tasks when five or six different stimuli exist. These guidelines apply specifically to color also when colors represented a value or meaning. Therefore, to avoid incurring costs only a handful of colors should be used to represent colors that must be categorized.

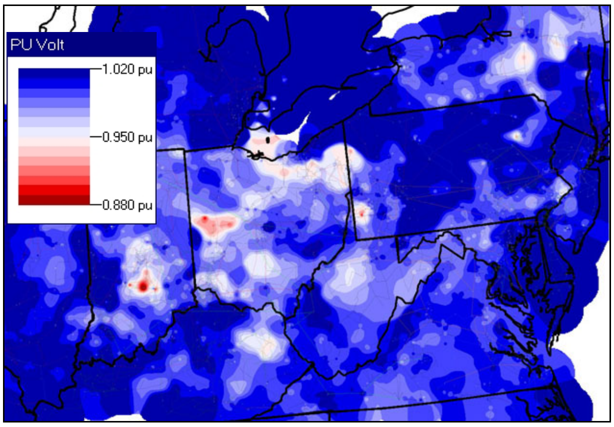

Figure 7: Pre-Blackout 115-230 kV Voltage Contour

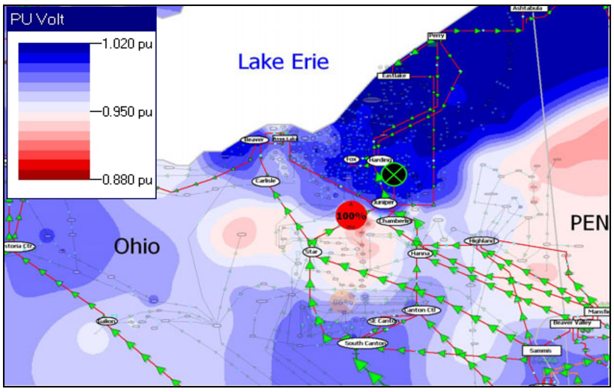

Figure 8: Northeast Ohio Voltage Contour at 15:05

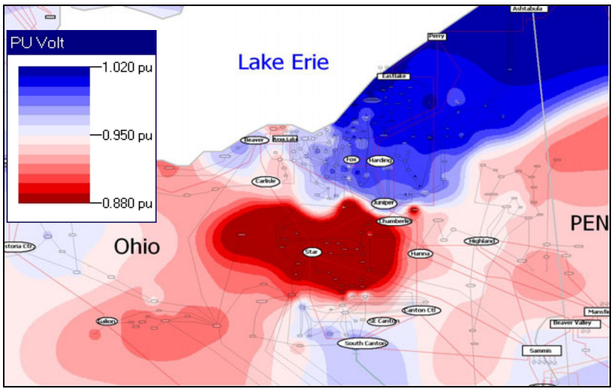

Figure 9: Northeast Ohio Voltage Contour at 15:51

Another issue associated with the use of color in displays is that no natural continuum exists. There is no inherent meaning that guides people to judge one color being greater or less in value along some dimension [12]. Therefore, the use of color in displays can be affected both positively and negatively by population stereotypes. Some colors tend to have established meanings associated with them. For example, western societies tend to associate the color red with stop, warning or danger. The color green is used often to mean go, all clear, or normal. Displays that use colors to represent these common meanings profit from the redundancy. Then again, erroneous use of colors may create conflicting meanings. For example, a power system display could be made to represent voltages that are below a certain voltage threshold by surrounding the low voltage area with a red contour (i.e., to indicate a warning/dangerous condition). However, another common meaning of the color red is to indicate heat and warmth (i.e., higher values) , while blue tends to indicate cold (i.e., lower values). Hence a conflict in meaning could develop if red is used to indicate lower values, such as in Figure 7. Therefore standardization of color contouring mappings between utilities should be developed.

Finally, the issue of clutter is often involved with the use of color. Color, if not used carefully, can unintentionally conceal or hide important aspects of a display. This occurs by overlapping, blending, and inundating the display with multiple colors. For instance, red text would be lost if it was displayed on a red background. This is a particular concern with contours in which the background can take on a number of different colors, perhaps inadvertently obscuring other import values. This issue can be resolved by using contour color mappings that do not include other color used on the one-line.

5 VISUALIZATION AND CHOICE OF ACTION

Once the problem has been diagnosed the next step in decision making is to choose a course of action. During times of normal operation a number of advanced network analysis tools, such as power flow, contingency analysis and OPF, are available to help in decision making. However, as mentioned earlier, it is likely few of these tools would be available during an extreme emergency. Developing more robust tools for such times is an area in need of additional research.

One promising approach is to calculate sensitivity values based solely upon a “dc power flow” representation of the system (pp. 108, [22]), in which the relationship between the bus power injections and the bus voltage angles is given by

$$\boldsymbol{\theta} = \left[\mathbf{B'}\right]^{-1} \mathbf{P} \tag{1}$$

where $\boldsymbol{\theta}$ the vector of bus voltage angles (e.g., the state variables – voltage magnitudes are assumed to be one per unit in the dc power flow), **P** is the vector of bus power injections, and **B’** is the negative of the bus susceptance matrix. The entries of **B’** can be determined from the known transmission line impedance values, and the line/breaker topology, which is available from SCADA. Hence it is independent of the system voltage state. The importance of (1) is not that we can calculate $\boldsymbol{\theta}$; in general we can’t since usually not all the entries in **P** are known. Rather, its importance is it can be used to get important sensitivity information on quantities that depend upon the state variables, such as the sensitivity of a desired transmission line flow to changes in the bus power injections. This is information that is critical to determining corrective control actions, such as where and how much generation should be changed and/or load should be shed to remove a transmission line overload. Visualization could be used to rapidly convey the best network locations for these control actions.

Referring again to the August 14th blackout, the final report concluded both that the loss of the Sammis-Star 345 kV line at 16:05 EDT triggered the ultimate cascade and that this loss could have been prevented by shedding 1500 MWs in the Cleveland-Akron area (pp 45, 70 of [2]). Since this line was overloaded for about twenty minutes before it tripped, there was time for operator response. But they needed to know where load shedding would be most effective. To help provide this information, Figure 10 shows a contour of the sensitivity of the real power flow on this line to changes in bus power injection. To allow simultaneous display of power flow and contour information a brown-purple color contour is used, with the here with the purple shaded areas indicating locations in the system where increasing generation and/or dropping load would have resulted in a decreased line loading, while the brown shaded areas indicate locations where decreasing generation and/or increasing load would have been beneficial. Importantly, the Figure 10 data could be calculated and displayed quickly, without the need of an SE solution.

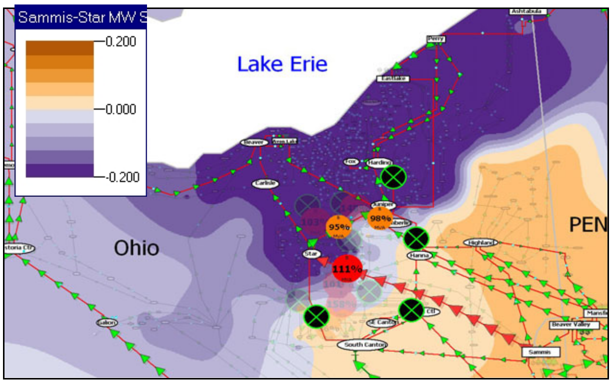

Figure 10: DC Power Flow Sensitivities of MW Flow on Sammis-Star 345 kV Line to Power Injections

Of course, these sensitivities are dependent upon the assumed topology, and topological errors could cause errors. But unless the topological errors are in the immediate vicinity of the monitored element the errors should be slight. Also, provided **B'** is full rank, a condition that should always be true, these sensitivities can always be calculated. We can easily imagine a number of extensions to this example, such as coupling this type sensitivity information with information about what controls (generators and loads) actually are available. With an interactive environment a power system operator could quickly determine the location of potential controls for different line overloads.

6 PUTTING IT ALL TOGETHER AND CONCLUSION

Visualization can play a crucial role in reducing the risk of future blackouts by helping control room personnel to quick assess a potentially rapidly changing system state, and by helping them to formulate corrective control actions. Of course how the visualizations could used would need to be tailored to the unique needs of each control center. One approach might be to have a mapboard type projection at the front of the control room. During normal operation this projection could be used to show the traditional static mapboard information, such as line status information. But during system emergencies (and training sessions) the projection could be reconfigured into a number of smaller displays, with one showing the transmission flows, one a system voltage contour, and perhaps a third reserved the sensitivity analysis described in the previous section. For those who prefer a static mapboard, the mapboard information could be supplemented through the use of large, high resolution LCD panel display systems or projection systems. Of course, all displays would also be accessible on the individual operator monitors as well.

REFERENCES

[1] P. Fairley, "The unruly power grid," *IEEE Spectrum*, vol. 41, August 2004, pp. 22-27.

[2] "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," U.S. Department of Energy, April 2004.

[3] "The August 14th 2003 Blackout One Year Later: Actions Taken in the United States and Canada to Reduce Blackout Risk," U.S. Department of Energy, August 2004.

[4] J.F. Hauer, J. E. Dagle, "Consortium for Electric Reliability Technology Solutions Grid of the Future White Paper on Recent Reliability Issues and System Events," U.S. Department of Energy, December 1999.

[5] M. Kobayashi, "What we must learn from 1995: the great Kobe-earthquake considerations on the distribution power poles," IEEE *Trans. Power Delivery*, vol. 12, July 1997, pp. 1368-1373.

[6] G.K. Morison, B. Gao, P. Kundur, "Voltage stability analysis using static and dynamic approaches," *IEEE Trans. Power Systems*, vol. 8, August 1993, pp. 1159-1171.

[7] A. Kurita and T. Sakurai, "The Power System Failure on July 23, 1987 in Tokyo," *Proc. 27th IEEE Conf. on Decision and Control*, Austin, TX, Dec. 1988

[8] D.N. Kosterev, C.W. Taylor, W.A. Mittelstadt, "Model validation for the August 10, 1996 WSCC system outage," *IEEE Trans. Power Systems*, vol. 14, August 1999, pp. 967-979.

[9] "Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy," UCTE, April 2004.

[10] "Interim Report of the U.S. Department of Energy's Power Outage Study Team," U.S. Department of Energy, January 2000; available on-line at http://www.eh.doe.gov/post/interim.pdf.

[11] A.G. Phadke, "Synchronized phasor measurements – a historical perspective," *Proc. IEEE PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific*, October 2002, pp. 6-10.

[12] C.D. Wickens, J.G. Holland, *Engineering Psychology and Human Performance*, Third Edition, 2000, ISBN: 0-321-04711-7.

[13] T.J. Overbye, P.W. Sauer, C.M. Marzinzik, and G. Gross, "A User-Friendly Simulation Program for Teaching Power System Operations," *IEEE Trans. on Power Sys.*, pp. 1725-1733, November, 1995.

[14] C. Ware, *Information Visualization*, 2004, ISBN: 1-55860-819-2.

[15] P.M. Mahadev, R.D. Christie, "Minimizing User Interaction in Energy Management Systems: Task Adaptive Visualization," *IEEE Transactions on Power Systems*, vol. PWRS-11, pp. 1607-1612, August 1996.

[16] T.J. Overbye, G. Gross, M.J. Laufenberg and P.W. Sauer, "Visualizing Power System Operations in the Restructured Environment," *IEEE Computer Applications in Power*, pp. 53-58, January 1997.

[17] D.A. Wiegmann, G.R. Essenberg, T.J. Overbye, Y. Sun, "Human factors aspects of power system flow animation," to *appear IEEE Trans. on Power Systems*.

[18]. D. Weber and T. J. Overbye, "Voltage contours for power system visualization," *IEEE Trans. on Power Systems*, vol. PWRS-15, pp. 404-409, February, 2000,

[19] C.A. Brewer, "Guidelines for use of the perceptual dimensions of color for mapping and visualization," *Proc. International Society for Optical Engineering (SPIE)*, San Jose, February 1994, vol. 2171, pp. 54-63.

[20] T.J. Overbye, D.A. Wiegmann, A.M. Rich, Y. Sun, "Human factors aspects of power system voltage contour visualizations," *IEEE Trans. on Power Systems*, vol. PWRS-18, pp. 76-82, February 2003.

[21]T.J. Overbye, Y. Sun, R.P. Klump, J.D. Weber, "Interactive 3D visualization of power system information," *Electric Power Components & Systems*, pp. 1205-1215, December 2003.

[22] A.J. Wood, B.F. Wollenberg, *Power Generation Operation and Control*, John Wiley & Sons, Inc., New York, NY, 1996.